BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B70 03012

SUBJECT: Calibration of the Descent Propulsion System Propellant Tanks and Propellant Quantity Gauging System - Case 310

DATE: March 5, 1970

FROM: K. P. Klaasen

ABSTRACT

Evaluation of a proposal to calibrate the LM Descent Propulsion System (DPS) propellant tanks and the Propellant Quantity Gauging System (PQGS) in the tanks shows that a pre-mission calibration of the PQGS from 10% propellant remaining to depletion could result in an increase of about 90 lb. in LM payload capability on future missions. This increase in payload capability is a result of an assumed reduction of 1/3 in the dispersions on I_{sp} and mixture ratio and requires no change in the quantity of propellant loaded or the LM dry weight. The major cost of this calibration lies in increasing propellant loading time at Cape Kennedy from 24 hr. to 30-35 hr.; however, it is understood that no increase in the total countdown time is required. A total calibration of the DPS tanks and PQGS rather than the 10% calibration would buy a maximum of only about 4 lb. more payload capability at the cost of increasing propellant loading time to 40-50 hr.

(NASA-CR-112743) CALIBRATION OF THE DESCENT PROPULSION SYSTEM PROPELLANT TANKS AND PROPELLANT QUANTITY GAUGING SYSTEM (Bellcomm, Inc.) 11 p

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MEMORANDUM FOR FILE

INTRODUCTION

It has been asserted that a physical calibration of the Descent Propulsion System (DPS) propellant tanks and the Propellant Quantity Gauging System (PQGS) in the tanks would provide a relatively easy and inexpensive means of increasing the performance capability of the Lunar Module (LM)[1]. Current inaccuracies in our knowledge of the quantity of propellant actually loaded in the DPS tanks and the quantity of propellant remaining at and near touchdown result in the persistence of large allocations in the descent propellant budget to cover for dispersions. The proposed calibration would result in better knowledge of the quantity of propellant in the DPS tanks and thus could lead to a reduction in some of the current descent propellant budget allocations. A reduction in the amount of propellant budgeted for dispersions would leave more propellant free to be used to carry greater payloads or to increase propellant margin.

The proposed calibration of the DPS tanks and the PQGS would be performed during the loading of the fuel and oxidizer at Cape Kennedy. It consists of a series of loads and off-loads of propellant using a weigh tank to measure the quantity of propellant loaded. The calibration could take one of two forms: either a total calibration of the tanks and PQGS or a calibration of the system from 10% propellant remaining to depletion. The major cost of performing the calibration would be in increased loading time at the Cape. Current loading time is 24 hr. Loading time is estimated to be 40-50 hr. for a total calibration and 30-35 hr. for a 10% calibration; however, no increase in the total countdown time is necessitated in either case.

LM DESCENT PROPELLANT BUDGET

In order to determine quantitatively what performance benefits can be achieved through calibration, it is necessary to examine how descent propellant is currently budgeted by MSC. A typical LM descent budget is presented in Table 1 for consideration.[2] Table 2 shows the individual contributions to the total quantity allocated for 3σ dispersions. The performance benefits to be derived from calibration will take the form of reductions in the quantities which are considered unusable or are required to cover for dispersions, thus increasing the propellant which is available to be used for delta-V without changing the quantity of propellant loaded or the LM dry weight. An increase of 1 lb. in the quantity of propellant usable for delta-V could be used either to provide a 1 lb. increase in propellant margin without changing the LM payload or to carry about 2 lb. more payload without changing the propellant margin.

EVALUATION OF POSSIBLE CALIBRATION BENEFITS

An evaluation of the possible effect of calibration of the DPS tanks and the PQGS on each of the items in the propellant budget follows. Most of the items in the budget will be unaffected by calibration; however, reductions can be expected in the allocations for outage and minus 3σ dispersions. The budget items are evaluated in a different order than they are listed in Table 1 so that the discussion might progress more logically.

1. More accurate value for trapped and unavailable propellant.

The amount of propellant which is considered to be trapped in the engines, lines, and tanks and is, therefore, not available for use has been determined in the past by a calculation rather than an actual measurement. In three tests at the White Sands Test Facility, the DPS engine burned 11, 15 and 18 seconds after the propellant in the tanks had reached the calculated unusable level.[1] At a propellant burning rate of 9.3 lb./sec., the minimum extra burn time of 11 sec. represents 102 lb. of usable propellant that is presently considered unusable. A more accurate value for the amount of propellant which is actually trapped and unavailable could be obtained from a measurement of the trapped propellant after engine shut-down. However, this measurement would require initiation of a new test program and would not be accomplished by the proposed calibration at the Cape.

2. Reduction in propellant allocation for low level sensor uncertainty.

The low level sensor (LLS) is a part of the PQGS. It causes a warning light to be lit on the spacecraft control panel when the amount of propellant remaining in any tank reaches 5.6%

of its capacity. It is believed from flight experience that the low level light has come on before the propellant actually reached the 5.6% point, presumably because of propellant sloshing which caused the LLS to be uncovered too soon. Present LLS accuracy assuming no propellant sloshing is on the order of ±.2% of the capacity of each tank or about ±4 sec. of burn time.[3] The allocation in the propellant budget for LLS uncertainty is based on this accuracy. The 68.7 lb. of propellant allocated represent 7.4 sec. of burn time which covers the LLS inaccuracy plus some pad. Since calibration of the PQGS is not expected to give accuracy much better than ±.2%, no reduction in the LLS uncertainty allocation is expected from calibration.

In the area of real time knowledge of the amount of propellant remaining during LM descent, LLS inaccuracies become more important. According to present mission rules, the LLS signal takes priority over the PQGS reading as an indicator of remaining propellant because the time to the touchdown or abort decision is based on the time since the LLS light is lit. Thus, should the LLS be activated early due to propellant sloshing, any propellant remaining above 5.6% of capacity at that time becomes essentially unusable. In such a case, readings from a calibrated PQGS which have had the effects of sloshing reduced by some sort of averaging technique could be used rather than the LLS signal to give more accurate knowledge of the true quantity of propellant remaining. However, proposed measures designed to minimize propellant sloshing and/or its effects on the LLS could prove to be effective means of reducing real time LLS signal inaccuracies thus nullifying any benefits of calibration in this area.

3. Reduction in minus 3σ dispersion allocation.

One contribution to the 3σ dispersion which might be reduced by calibration of the DPS tanks is the dispersion on fuel and oxidizer loading. Loading dispersions are ±.25% of the tank capacity or a total of about ±17.7 lb. of fuel and ±28.1 lb. of oxidizer in the propellant budget under consideration. It is uncertain just how far a tank calibration could reduce these dispersions. If they were to be reduced to zero, however, the RSS value of all dispersions would be reduced by only about 2 lb. Reduction of loading dispersions would require total tank calibration rather than the 10% calibration, and the very slight increase in performance which might be gained does not seem to justify total tank calibration.

The accurate knowledge of the amount of propellant remaining at touchdown which would be made available by calibration of the PQGS could lead to possible reductions in the dispersions on I_{sp} and mixture ratio. Post flight analyses based on the amounts of fuel and oxidizer remaining could lead to better knowledge of the actual I_{sp} and mixture ratio of the DPS engine on that mission. Statistical analyses on the data accumulated as missions are flown could result in a reduction in future I_{sp} and mixture ratio dispersions. Knowledge of the propellant quantities remaining at touchdown would require only the 10% calibration of the PQGS.

The present accuracy of the PQGS in each LM is not known. However, the accuracy specified for PQGS qualification is ±1% of the tank capacity. This uncertainty itself corresponds to ±112 lb. of oxidizer and ±71 lb. of fuel in the example propellant budget. Such inaccuracy in our knowledge of the propellant remaining at touchdown precludes a calculation of the actual I_{sp} or mixture ratio of the engine on that mission with enough accuracy to reduce the dispersions since the gauging inaccuracy is nearly as large as the effects due to present dispersions. Since the repeatability of the PQGS is estimated to be between ±.1% and ±.25%, the improved measurement accuracy which would result from a calibration of the PQGS in the tanks would lead to a more accurate and useful calculation of the engine I_{sp} and mixture ratio for that mission.

Again it is unknown what if any reductions could be made in the present dispersions. The minus 3σ dispersions in the example propellant budget are -3.98 sec. on I_{sp} resulting in a 158.5 lb. reduction in propellant usable for delta-V and +.02724 on mixture ratio resulting in a 114.4 lb. reduction in propellant usable for delta-V. Reduction of these dispersions to zero would reduce the total minus 3σ dispersion by about 49 lb. for I_{sp}, 24 lb. for mixture ratio, and 78 lb. for both. In practice, however, these dispersions will never be reduced to zero. A more realistic projection would be to assume, for example, a reduction of 1/3 in the dispersions to -2.65 sec. on I_{sp} and +.01816 on mixture ratio. Under this assumption, the total minus 3σ dispersion would be reduced by about 26 lb. for I_{sp}, 16 lb. for mixture ratio, and 43 lb. for both.

In the example budget, the requirement on the probability of propellant non-depletion is 0.99999 (or 4.27σ). Thus, any reduction in the minus 3σ requirement would be multiplied by 1.423 to give the corresponding increase in propellant usable for delta-V. However, MSC is implementing changes to the descent propellant budget which include allocating propellant to cover dispersions only up to 3σ. Therefore, the increases in propellant usable for delta-V which are claimed in this memorandum will simply be set equal to the reduction in the minus 3σ propellant requirement as would be the case if propellant were allocated to cover dispersions only up to minus 3σ.

4. Reduction in outage allocation.

Outage is the excess fuel or oxidizer remaining at the time at which one of these components of propellant is depleted. The outage allocation in the propellant budget is chosen so that, based on the nominal mixture ratio and its dispersions and on the quantity of nominally deliverable fuel and oxidizer, 50% of the time the excess fuel or oxidizer will be less than this outage allocation. This allocation is 39.1 lb. in the example propellant budget. Since the ratio of deliverable oxidizer to deliverable fuel is generally not exactly equal to the nominal mixture ratio, there usually exists some nominal outage. In the case of the example propellant budget, for instance, the nominal outage is 31.4 lb. of fuel. As the mixture ratio dispersions decrease, the outage allocation will approach the nominal value of outage. Thus, for the budget under consideration, a reduction in mixture ratio dispersions to zero would yield the maximum reduction in the outage allocation from 39.1 lb. to 31.4 lb. or a decrease of 7.7 lb.

5. Reduction in the amount to be off-loaded.

The nominal amount of fuel or oxidizer to be off-loaded is a function only of the nominal mixture ratio and the nominal tank capacity and is determined so as to optimize the amount of usable propellant. Neither of these will be affected by the additional knowledge gained from calibration of the DPS tanks or PQGS. Errors may exist between the nominal amount to be off-loaded and the amount which actually should be off-loaded in any given case because of dispersions on tank loading and mixture ratio; however, these off-loading errors are covered in the dispersion allocations for loading and mixture ratio.

6. Reduction in valve pair malfunction allowance.

The propellant allocation for a valve pair malfunction is intended to compensate for shifts in the mixture ratio off nominal due to such a malfunction. The allocation is determined on the basis of the nominal propellant capacity and mixture ratio and the predicted mixture ratio shifts resulting from a valve pair malfunction and will not be affected by any reduction in dispersions which might result from calibration. The propellant budget changes being implemented by MSC include deletion of this item from the budget.

CONCLUSIONS

The major benefit to be derived from the proposed calibration procedure lies in the improvement in future mission planning which would result from more accurate knowledge of past mission performance. A calibration of the PQGS from 10% propellant remaining to depletion would provide a more accurate measure of the fuel and oxidizer remaining at touchdown which could lead to better estimates of engine performance and possible reductions in the values of the dispersions on I_{sp} and mixture ratio. The maximum possible gain from such a calibration would be reduction of I_{sp} and mixture ratio dispersions to zero resulting in an increase in the quantity of propellant usable for delta-V of about 78 lb. from a reduced dispersion allocation and about 8 lb. from a reduced outage allocation. In this ideal case, LM payload capability would be increased by about 172 lb. A more reasonable estimate of the expected gain would be a decrease of 1/3 in I_{sp} and mixture ratio dispersions resulting in an increase in propellant usable for delta-V of about 45 lb., 43 lb. from a reduced dispersion allocation and 2 lb. from a reduced outage allocation. This would produce an increase in payload capability of 90 lb.

The 10% calibration would increase the propellant loading time at the Cape from 24 hr. to 30-35 hr. A total calibration of the DPS tanks and PQGS rather than the 10% calibration would increase the propellant loading time to 40-50 hr. and would provide a maximum additional increase in propellant for delta-V of only about 2 lb. through a reduction in the loading dispersion and would increase the payload capability only about 4 lb.

The calculated increases in propellant usable for delta-V are based on an example propellant budget. The changes in the propellant allocations are dependent on this baseline budget. However, the example budget represents a typical descent propellant budget, and the calculated changes are also expected to be typical for both H and J mission LM hardware.

K.P. Klaasen

2013-KPK-jab

K. P. Klaasen

Attachments
References
Tables 1 and 2

REFERENCES

1. "LM-5 (Apollo 11) Descent Propulsion System Propellant Remaining Study," Boeing Co. presentation to W. E. Stoney, Jan. 15, 1970.

2. "Revision I to Apollo Spacecraft Weight and Mission Performance Definition (December 12, 1967)," Manned Spacecraft Center, May 5, 1969.

3. "Volume II LM Data Book - Appendix LM-6," Grumman Aerospace Corporation, Nov. 13, 1969.

	Fuel, lb.	Oxidizer, lb.	Total, lb.
System capacity	7057.1	11,186.7	18,243.8
Trapped and unavailable	-50.7	-172.8	-223.5
Available capacity	7006.4	11,013.9	18,020.3
Off-loaded	-91.3	0.0	-91.3
Nominal deliverable	6915.1	11,013.9	17,929.0
Low level sensor			-68.7
Outage			-39.1
Valve pair malfunction			-60.1
Usable			17,761.1
Minus 3σ			-282.7
Performance uncertainty (1.27σ)			-118.8
Usable for delta-V			17,359.6

TABLE 1 - TYPICAL LM DESCENT PROPELLANT BUDGET

(Data from Reference 2)

Variable	Value	ΔFuel usable, lb	Δ Oxidizer usable lb	ΔTotal propellant usable, lb	Δ Propellant required, lb	ΔTotal propellant remaining, lb
Fuel loading (0.25%)	±17.7 lb	0.0	0.0	0.0	±9.6	±9.6
Oxidizer loading (0.25%)	±28.1 lb	±17.6	±28.1	±45.7	±15.3	±30.4
Fuel trapped	±4.0 lb	0.0	0.0	0.0	0.0	0.0
Oxidizer trapped	±9.0 lb	±5.6	±9.0	±14.6	0.0	±14.6
I_{sp}	±3.98 sec	0.0	0.0	0.0	+158.5 -155.9	+158.9 -158.5
ΔV	±119 ft/sec	0.0	0.0	0.0	+200.9 -203.4	+203.4 -200.9
Sep weight	±9.6 lb	0.0	0.0	0.0	±5.2	±5.2
Non-delta V consumables Weight	±29.5 lb	0.0	0.0	0.0	±10.0	±10.0
Mixture ratio	+.02724 -.02736	-	-	+39.1 -114.4	0.0	+39.1 -114.4
RSS						+261.8 -282.7

TABLE 2 - LM DESCENT 3σ PERFORMANCE DISPERSIONS

(Data from Reference 2)

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